232

356

CONFIDENTIAL UNCLASSIFIED

Copy

RM E55I14

NACA RM E55I14

N63-12528
code-1

NACA

RESEARCH MEMORANDUM

PERFORMANCE OF A SINGLE FUEL-VAPORIZING COMBUSTOR WITH SIX INJECTORS ADAPTED FOR GASEOUS HYDROGEN

By Jerrold D. Wear and Arthur L. Smith

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

XEROX $ 2.60 ph

MICROFILM $ 0.89 mf

CLASSIFICATION CHANGED TO
UNCLASSIFIED
AUTHORITY NASA LIST #1, Dec 1, 1962

G. L. L.

CLASSIFIED DOCUMENT - TITLE UNCLASSIFIED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
November 30, 1955
Reclassified May 29, 1959

CONFIDENTIAL UNCLASSIFIED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PERFORMANCE OF A SINGLE FUEL-VAPORIZING COMBUSTOR WITH SIX INJECTORS ADAPTED FOR GASEOUS HYDROGEN*

By Jerrold D. Wear and Arthur L. Smith

SUMMARY

In preparation for tests with hydrogen fuel in a full-scale turbojet engine using an annular fuel-vaporizing combustor, an investigation was conducted in a single tubular combustor of similar design to evolve a satisfactory fuel-injection system. The performances of six different fuel-injector designs in the single combustor were determined. The combustor was operated over a range of inlet-air pressures from 5.3 to 24.0 inches of mercury absolute and inlet-air reference velocities from 60 to 100 feet per second.

The combustion efficiencies obtained with the six configurations varied from about 65 to 95 percent for a combustor temperature-rise range of 200° to 1400° F. At a temperature rise of 1200° F (near-rated engine conditions), the spread in efficiencies of the six configurations was about 5 percent. Efficiencies in the range of 65 to 85 percent were obtained at operating conditions beyond the burning range of conventional jet fuels.

A fuel-injector configuration that fed only gaseous hydrogen fuel into the standard liquid-fuel-vaporizing tubes generally gave the highest efficiencies. This configuration minimized the possibility of combustion in the fuel-vaporizing tubes and could be easily adapted to the full-scale engine combustor.

INTRODUCTION

Increased operational altitudes are required for military applications of turbojet-powered aircraft. Consequently, it is important to determine the effect of extreme altitude on the performance of a turbojet engine. One factor limiting operation at high altitudes is the performance of the combustor. Preliminary studies in a single turbojet combustor (ref. 1) show that a special fuel, gaseous hydrogen, can be expected to burn with higher combustion efficiencies and at considerably lower pressures, corresponding to higher altitudes, than conventional

*Title, Unclassified.

jet fuel. In addition, an analysis (ref. 2) shows that the use of liquid hydrogen, because of its high heating value per unit weight, can also be expected to provide large gains in over-all aircraft performance at high altitude. For example, for a flight altitude of 80,000 feet, flight Mach number of 2.5, and a gross aircraft weight of 30,000 pounds, liquid hydrogen will increase the combat radius of a fighter aircraft about 70 percent over that obtained with JP-4 fuel. The analysis is based on anticipated performance of future engines and aircraft.

In view of these results, it was considered important to conduct high-altitude engine tests with hydrogen fuel. The engine chosen for these tests has an annular combustion chamber with fuel-vaporizing tubes inside the chamber. Before a highly reactive fuel was used in the full-scale engine, with its large and expensive auxiliary equipment, safe techniques for supplying the fuel to the engine and for injecting it into the combustion chamber were determined in small-scale apparatus. The methods of handling and supplying gaseous hydrogen described in reference 1 were satisfactory. However, information was sought on such items as

(1) Can the combustor be safely ignited?

(2) How will the combustor operate with a gaseous fuel?

(3) Will combustion take place inside the fuel-vaporizing tubes?

Combustion inside the vaporizing tubes would probably cause failure with consequent damage to the turbine, and changes in combustion efficiency and exhaust temperature profile.

Accordingly, preliminary tests were conducted in a single tubular fuel-vaporizing combustor of the same basic design used in the full-scale engine chosen for the initial tests. The inlet-air pressure was varied from about 5 to 24 inches of mercury absolute, and inlet-air reference velocities from about 60 to 100 feet per second. These inlet-air conditions, except for temperature, simulate altitudes from 60,000 to 95,000 feet at a Mach number of 0.8 for the full-scale engine considered.

In order to obtain information about ignition, combustion, and durability, six different fuel-injector configurations were constructed and tested with gaseous hydrogen. Past experience has indicated that the results obtained from these designs would furnish enough of the desired information without an extensive development program. Ignition test results at one altitude windmilling condition are given. Other results are presented to indicate the low-pressure performance characteristics (combustion efficiency, combustor temperature rise, and combustor pressure drop) obtained with gaseous hydrogen and the various injector configurations. Brief comparisons are made between the combustion efficiencies obtained with hydrogen and with a JP-4 fuel.

APPARATUS

Combustor Installation and Instrumentation

The installation of the single tubular fuel-vaporizing combustor is shown schematically in figure 1. Air having a dewpoint of either -20° or -70° F was supplied to the combustor from the laboratory supply system; the exhaust gases were fed to the laboratory altitude-exhaust system. Air flow was measured with a square-edged orifice plate installed according to A.S.M.E. specifications and located upstream of the flow regulating valves. The combustor inlet-air temperature was regulated by means of electric heaters.

A diagrammatic cross section of the combustor installation is shown in figure 2. The inlet and outlet transition sections are 1/6 sectors, each with an annulus corresponding to that in the full-scale engine. The areas of the inlet and outlet 1/6-sector annuli are 0.0465 and 0.0501 square feet, respectively. The maximum inside diameter of the combustor housing is 6.002 inches (area of 0.1965 sq ft). The primer-fuel nozzle and igniter plug are also shown in figure 2. The nozzle orifice originally designed for liquid fuel was drilled out to 3/32 inch so that a sufficient flow of hydrogen could be obtained for ignition. The original diameter was about 1/64 inch. The flame and hot gases from this source pass through the primary-air admission plate and ignite the fuel entering the combustor through the main fuel injector.

The instrumentation planes and the location of temperature- and pressure-measuring instruments in these planes are presented in figure 2. Thermocouples and total-pressure probes were located at centers of equal areas. The combustor-inlet and -outlet temperatures were indicated on automatic balancing potentiometers. The thermocouple readings were taken as true readings and no corrections were made for recovery, conduction, or radiation. The inlet and outlet total-pressure data were obtained with manometers connected to 12 manifolded probes at plane A-A and 8 manifolded probes at plane D-D.

Fuel Supply System

A diagram of the fuel supply system is given in figure 4 of reference 1. Hydrogen was stored in 18 cylinders, manifolded together, at a pressure of about 2000 pounds per square inch. Each cylinder contained about 200 cubic feet (at standard atmospheric conditions) of hydrogen. The hydrogen was drawn from one or more of the cylinders through a reducing valve, filter, rotameter, throttle valve, check valve, and into the combustor. A relief valve and pressure switch, vented to the atmosphere, were installed to protect the system against excessive pressures. Analysis indicated the hydrogen was about 97 mole percent pure; the other 3 percent was mostly nitrogen.

Fuel flow rates to the combustor were measured by rotameters. The rotameters were calibrated with air at pressure and temperature conditions to give the same fluid densities as those of the test fuel at the test conditions. Appropriate density corrections were then applied to the rotameter measurements.

Fuel Injectors

Standard liquid-fuel injector. - A cut-away view of a combustor with the standard fuel injector and standard method of primary-air admission is shown in figure 3. (The primer-fuel nozzle and igniter plug are not shown.) After ignition of the primer fuel, the main fuel is started and fed through the four small main fuel-injector tubes into the fuel-vaporizing tubes, along with some primary air. The main fuel then ignites as it comes from the fuel-vaporizing tubes into the combustion zone. The heat generated in the combustion zone heats the fuel-vaporizing tubes so that, finally, only vaporized fuel enters the combustion zone.

It was thought that some modifications might be needed in the fuel injectors in order to burn gaseous hydrogen in the liquid-fuel vaporizing combustor. Because time for the investigations was limited, six injector configurations were designed and constructed before the tests were started. No extensive development program of injectors was attempted. Construction details of the various injector configurations are shown in figure 3.

Configuration 1. - Configuration 1 was the same as the standard injector, except that the orifices in the four small fuel tubes of the injector were drilled out to a diameter of 1/16 inch to permit as much gaseous fuel flow as possible.

Configuration 2. - Configuration 2 is the same as configuration 1, without the four fuel-vaporizing tubes. Because hydrogen is very reactive and has a wide flammability limit, it was thought that combustion might take place in the fuel-vaporizing tubes of configuration 1 where air and fuel enter the tubes together. Combustion in a tube would probably cause it to fail with consequent damage to the turbine. Information obtained with configuration 2 would indicate the performance possible in case the engine had to be operated without the vaporizing tubes.

Configuration 3. - The small four-tube injector of configurations 1 and 2 was replaced by an injector that had four larger tubes that fitted into the standard fuel-vaporizing tubes. Very little air could enter the vaporizing tubes with the fuel. This configuration would permit the fuel-vaporizing tubes to be used with little possibility of internal combustion. The injector was designed to provide an adequate flow rate of hydrogen.

Configurations 4, 5, and 6. - In an effort to improve the combustion performance, a different method of fuel injection was designed for configurations 4, 5, and 6. A large single fuel tube injected the hydrogen perpendicular to the combustor axis, and no fuel-vaporizing tubes were used.

In configuration 4, the fuel was injected from six evenly spaced 1/16-inch-diameter holes drilled tangential to the inside of the tube. Very little air could enter the combustion zone along the outside of the tube.

Configuration 5 was similar to 4, except for two changes: (1) more air was admitted along the outside of the fuel tube and, (2) six more fuel delivery holes were drilled in the same plane of the tube as the six original holes and positioned so that the fuel jets from two adjacent holes would impinge. It was thought that this would give better mixing of fuel and air.

Configuration 6 used the same fuel delivery tube as configuration 5. The method of primary-air admission was changed by replacing the standard air admission plate with one containing two circular rows of holes drilled at an angle to the plate surface to give a swirling motion to the air. This configuration was designed to improve mixing between the fuel and air and to avoid over-enrichment of the primary zone as the fuel flow was increased.

PROCEDURE

The combustor was ignited by the igniter plug and primer fuel nozzle. After ignition of the main fuel, the plug was de-energized and the primer hydrogen fuel flow shut off.

The combustion performance of gaseous hydrogen fuel was determined at the following combustor operating conditions:

Inlet-air total pressure, in. Hg abs	Nominal air-flow rate, lb/sec	Nominal reference velocity, ft/sec (a)
5.3	0.125 .156 .167	60 75 80
6.9	0.163 .217 .258	60 80 95
11.0	0.260 .347 .434	60 80 100
24.0	0.566	60

[a]Based on combustor maximum cross-sectional area of 0.1965 sq ft measured at a plane 15 in. downstream of plane A-A, fig. 2.

The combustor inlet-air temperature was approximately 200° F for all tests listed in the table. The actual reference velocities obtained during the tests varied somewhat from the values listed because of difficulty in controlling low air-flow rates at low pressures.

At each of the combustor-inlet conditions, performance data were recorded over a range of fuel-air ratios. This range was limited by: (1) average combustor-outlet temperatures of approximately 1600° F, (2) altitude exhaust limitation, and (3) excessive pressure drop in the fuel injector, which limited the fuel flow. In some cases, because of fuel-flow or altitude-exhaust limitations, the maximum combustor temperature rise varied from 250° to 400° F. Several minutes were allowed for combustion to stabilize at each condition before the performance data were recorded. Methods of calculating combustion efficiency, inlet-air reference velocity, combustor pressure drop, and inlet-air and exhaust-gas densities are given in the appendix.

RESULTS

Ignition

A brief investigation was conducted to determine whether the combustor would ignite at the following altitude windmilling conditions:

Combustor-inlet total pressure, in. Hg abs	13.9
Combustor-inlet temperature, °F	-20
Combustor-inlet reference velocity, ft/sec	40
Fuel-injector configurations	3 and 4

The combustor ignited easily and quietly with a steady increase in exhaust temperature with increase in flow of the main fuel supply.

Combustion Efficiency

The combustor performance data obtained with gaseous hydrogen fuel in a single tubular fuel-vaporizing combustor are presented in table I.

The combustion efficiencies are plotted against combustor temperature rise in figure 4. Data are shown for the various fuel-injector configurations and combustor operating conditions. At low values of temperature rise, combustion efficiency almost always decreased with an increase in combustor temperature rise. One main exception to this trend occurred at a pressure of 11.0 inches of mercury absolute and reference velocity of 80 feet per second. With configurations 3, 4, 5, and 6 (figs. 4(c), (d), (e), and (f), respectively) where the fuel injector did not limit the fuel flow, the efficiencies generally leveled off at a temperature rise above 700° or 800° F. At low values of temperature rise (about 400° F), there was no general trend with inlet pressure, except that the highest pressure (24.0 in. Hg abs) generally gave the highest efficiency. Also at low values of temperature rise, the higher reference velocity at any one pressure generally gave the higher efficiency. For a temperature rise of about 1200° F, the data show an increase in efficiency with increase in pressure. The general efficiency range obtained with the various operating conditions varied from about 65 to 90 percent, with two or three test points approaching 95 percent.

Combustor Pressure Loss

Combustor pressure-loss coefficient $\Delta p/q$ (ratio of combustor total-pressure loss to combustor-inlet reference velocity pressure) is plotted against the ratio of inlet-air density to exhaust-gas density for configurations 1, 3, and 6 in figure 5. The data for these three configurations were considered representative of all configurations - configuration 1 was similar to the standard; number 3 used larger fuel-injector tubes; and number 6 incorporated modifications in both fuel-injection and primary-air-admission design.

The pressure-loss coefficient has been used in previous investigations to correlate data obtained over a wide range of operating conditions. The present data show a considerable spread in $\Delta p/q$ with a change in operating conditions. At a density ratio of 1.0 (cold flow), the extrapolated values of $\Delta p/q$ varied from about 20 to 35. At a density ratio of 2.4, $\Delta p/q$ varied from 35 to about 50 for each of the configurations. There seemed to be no general trend in $\Delta p/q$ with velocity at any one pressure. Although the differences were small, configuration 3 gave slightly higher pressure losses than configurations 1 and 6.

DISCUSSION

Combustion Efficiency

The combustion efficiencies obtained with the six injector configurations are compared in figure 6 where efficiency is plotted against combustor-inlet total pressure. The data of figures 6(a) and (b) are cross-plotted from figure 4 for a constant combustor temperature rise of 1200° and 400° F, respectively, and a reference velocity of 60 feet per second. Figure 6(c) shows data obtained with reference velocities of 75 to 100 feet per second and at a temperature rise of 400° F. The temperature rise of 1200° F represents near-rated engine speed conditions, and the 400° F value represents part-throttle, lean fuel-air-ratio operation.

At a temperature rise of 1200° F (fig. 6(a)), the largest difference in efficiency among all the configurations was about 5 percent and occurred throughout the pressure range. Configuration 3 generally showed as high or the highest efficiencies. The efficiency values varied from about 70 percent at low pressure to 89 percent at a pressure of 24 inches of mercury. At a temperature rise of 400° F (fig. 6(b)), the efficiencies were somewhat higher and differences in efficiencies were greater, varying from about 9 to 23 percent over the pressure range. Configuration 3 gave the highest efficiencies except for the pressure of 6.9 inches of mercury. At higher reference velocities (fig. 6(c)), configuration 3 gave efficiencies that were the highest at two pressures and were within 3 percent of the highest at the other pressure.

For most of the operating conditions, efficiency decreased with increase in temperature rise with all the configurations. This indicates over-enrichment of the primary combustion zone or poor fuel and air mixing. In some cases as the temperature rise was further increased, the efficiencies leveled off or increased slightly. Another indication of poor fuel and air mixing is shown by the increased efficiency with increase in inlet reference velocity at any one pressure condition (see figs. 4 or 6(b) and (c)).

Figure 7 presents a limited comparison of efficiency data obtained with JP-4 liquid fuel and with gaseous hydrogen in a vaporizing combustor at a constant temperature rise of 1200° F. The data are given in table II. Combustion efficiency is plotted against the correlating parameter V_r/p_iT_i (ref. 3) where V_r is the reference air velocity, p_i the inlet-air pressure, and T_i the inlet-air temperature. The JP-4 data are from reference 4 and were obtained in the same model of the standard fuel-vaporizing combustor of this investigation; the hydrogen data were obtained with fuel-injector configuration 3. The efficiencies obtained with JP-4 decreased from about 82 to 70 percent as the correlating parameter increased from 50 to 82×10^{-6}; for this same range the efficiencies with hydrogen decreased from 89 to 85 percent. Extrapolation of the JP-4 fuel curve indicates that JP-4 fuel would not burn at a correlation parameter of 100×10^{-6}; at the same parameter, hydrogen burns with an efficiency of about 83 percent. Low values of efficiency, obtained with hydrogen, were mainly due to the severe operating conditions, some of which were beyond the burning range of conventional jet fuels.

The parameter V_r/p_iT_i of reference 3 predicts a decrease in combustion efficiency with an increase in inlet reference velocity (V_r). However, some of the data reported herein show an increase in efficiency with an increase in velocity at low values of combustor temperature rise; these data would not be properly represented by V_r/p_iT_i. Nevertheless, the comparisons shown in figure 7 are considered to be valid, since the data for the two fuels were obtained at similar reference velocities and at a high value of temperature rise.

Stability of Combustion

The data that have been presented show that gaseous hydrogen will burn in a liquid fuel-vaporizing combustor at pressures as low as 5.3 inches of mercury absolute with inlet reference velocities of 75 to 80 feet per second. Limitations in test facilities, combustor-outlet temperatures, and injector fuel-flow capacity prevented operation of the combustor at more severe conditions. From the observed stability of combustion, however, it is probable that satisfactory operation could have been maintained at even more severe conditions. No flame blow-out occurred at either the lowest or the highest fuel-air ratios investigated for any of the fuel-injector configurations.

Visual Observations of Combustion

During operation with the various fuel-injector configurations, combustion was observed through the windows shown in figure 2. Hydrogen burns with a nonluminous flame, and at low values of temperature rise there was no evidence that combustion was occurring. At high values of temperature rise the only evidence of combustion was the glowing of the combustor internal components. With the fuel-injector configurations that used the fuel-vaporizing tubes (1 and 3), the air entry cups on the primary-air admission plate (fig. 2) became red hot at a temperature rise above 700° or 800° F. About $1\frac{1}{2}$ inches of the downstream ends of the fuel-vaporizing tubes of injector 1 became a dull red at a temperature rise of about 700° F. With configuration 3, about 1/2 inch of the ends of the fuel-vaporizing tubes became bright red at a 1400° F temperature rise. When configurations 4, 5, and 6 were used, bright red hot spots appeared on the liner in the same plane as the small fuel delivery holes, which indicated that a jet of invisible flame was striking the liner wall. The fuel was issuing from the delivery holes with such velocity that it penetrated, while burning, through the primary zone to the wall. The special air admission plate used with configuration 6 (fig. 3) became a dull red at a temperature rise of about 1400° F. After 6 hours of operation, the fuel-vaporizing tubes showed no indication of extreme heat except at the downstream ends.

Best Configuration

The investigation was conducted to develop a fuel injector that would safely feed gaseous hydrogen fuel to a full-scale engine with a fuel-vaporizing combustor. No extensive development program was attempted. Configuration 3 generally gave the best efficiencies in the single combustor and appeared safe from any preburning in the fuel-vaporizing tubes. In addition, this configuration required very few changes to adapt it to the full-scale engine.

The fact that there were only small variations in efficiency among the various injector configurations at high values of temperature rise indicated that some other component of the combustor controlled performance. The upstream opening in the combustor dome (fig. 3) probably limited the air flow to the primary combustion zone. Therefore, any change in the fuel-injector configurations probably had only small effects on mixing and, hence, on performance. The small variations in combustor pressure drop obtained with the various configurations also indicated that the primary air flow was probably limited by the opening in the dome.

CONCLUDING REMARKS

The investigation reported herein was conducted to evolve a satisfactory fuel-injection system for injecting gaseous hydrogen into a liquid-fuel vaporizing combustor. A fuel-injector system that fed only gaseous hydrogen fuel into the standard liquid-fuel vaporizing tubes was chosen for full-scale engine tests because of its generally high efficiencies and its freedom from possible preburning in the vaporizing tubes. This configuration could be adapted to the full-scale engine with a minimum amount of modification. It was found that the performance of the combustor with gaseous hydrogen at severe engine operating conditions was relatively insensitive to design modifications in the fuel-injector system. At high values of combustor temperature rise, representing near-rated engine operation, the spread in efficiencies among the various configurations was about 5 percent. Generally, the engine conditions for which low values of combustion efficiency (65 to 85 percent) were obtained were beyond the burning range of conventional jet fuels.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 21, 1955

APPENDIX - CALCULATIONS

Combustion efficiency. - Combustion efficiencies were calculated as:

$$\frac{\text{Actual enthalpy rise across combustor, per pound of air}}{(\text{Fuel-air ratio})(\text{Lower heat of combustion of fuel})} \times 100$$

From analysis, the fuel was about 97 mole percent hydrogen and 3 percent nitrogen. This was taken into account by considering the lower heat of combustion to be 50,024 instead of 51,571 Btu per pound. The enthalpies at the combustor inlet and outlet were determined from charts in figure 7 of reference 1, assuming that the following reaction occurred:

$$H_2 + \frac{O_2 + 3.78\ N_2}{2} + \text{excess air} \rightarrow H_2O + 1.89\ N_2 + \text{excess air}$$

The chart for the inlet enthalpies assumed that the hydrogen and air entered the combustor at the inlet-air temperature (plane B-B, fig. 2). The enthalpy of the exhaust gases was based on the arithmetical average indications of the 10 chromel-alumel thermocouples at plane C-C, figure 2.

Inlet-air reference velocities and combustor pressure drop. - The inlet reference velocities were calculated from the total pressure and temperature at planes A-A and B-B (fig. 2) and maximum cross-sectional area of the combustor (0.1965 sq ft). The combustor total-pressure drop was determined from the total-pressure measurements at planes A-A and D-D (fig. 2).

Inlet-air and exhaust-gas densities. - The inlet-air density was calculated from the total pressure and temperature at planes A-A and B-B (fig. 2); the static pressure at plane D-D and the average exhaust-gas temperature at plane C-C (fig. 2) were used for calculating the exhaust-gas density. The gas constant for the exhaust gases was assumed to be the same as for air.

REFERENCES

1. Jonash, Edmund R., Smith, Arthur L., and Hlavin, Vincent F.: Low-Pressure Performance of a Tubular Combustor with Gaseous Hydrogen. NACA RM E54L30a, 1954.

2. Silverstein, Abe, and Hall, Eldon W.: Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft. NACA RM E55C28a, 1955.

3. Childs, J. Howard: Preliminary Correlation of Efficiency of Aircraft Gas-Turbine Combustors for Different Operating Conditions. NACA RM E50F15, 1950.

4. Horstman, W. W.: Fuel Requirements of Pre-Vaporizing Type Gas Turbine Combustors - Materials Section. Eighth Quarterly Prog. Rep., Wood River Res. Lab., Shell Oil Co., Mar. 17, 1954. (Contract No. AF 33(616)-76.)

TABLE I. - PERFORMANCE OF SINGLE FUEL-VAPORIZING COMBUSTOR WITH GASEOUS HYDROGEN

Run	Combustor inlet total pressure, in. Hg abs	Combustor inlet temperature, °F	Inlet air flow, lb/sec	Combustor reference velocity, ft/sec	Fuel flow rate, lb/hr	Fuel air ratio	Average combustor outlet temperature, °F	Average combustor temperature rise, °F	Combustion efficiency, percent	Total pressure drop through combustor, in. Hg	Fuel nozzle pressure drop, psi	Pressure loss coefficient, $\frac{\Delta p}{q}$	Density ratio, $\frac{\rho_{in}}{\rho_{out}}$
(a) Fuel-injector configuration 1													
1	5.3	203	0.124	59.9	1.09	0.00244	555	352	71.6	0.3	25.9	36	1.70
2	5.3	201	.125	59.8	2.56	.00571	940	739	66.3	.4	63.4	48	2.45
3	5.3	201	.162	77.6	2.56	.00440	840	639	73.8	.7	63.2	50	2.58
4	5.3	202	.162	77.9	1.05	.00181	525	323	86.8	.5	25.8	35	1.79
5	6.9	201	.165	61.0	1.12	.00188	480	279	71.1	.4	25.7	35	1.58
6	6.9	203	.165	61.1	2.53	.00427	800	597	70.8	.4	62.2	35	2.14
7	6.9	200	.218	80.3	2.56	.00326	705	505	77.1	.8	62.6	41	2.30
8	6.9	197	.222	81.4	1.11	.00139	445	248	85.9	.7	25.8	35	1.68
9	11.0	198	.261	60.0	1.11	.00118	390	192	77.7	.6	23.6	34	1.42
10	11.0	199	.260	60.0	2.55	.00273	610	411	73.7	.6	60.2	34	1.80
11	11.0	203	.345	80.1	2.56	.00206	550	347	83.2	1.0	60.7	32	1.84
12	11.0	197	.345	79.4	1.10	.00088	350	153	80.6	.9	23.6	29	1.44
13	24.0	199	.568	60.1	2.57	.00125	440	241	91.7	1.1	54.7	29	1.49
(b) Fuel-injector configuration 2													
14	5.3	196	0.126	60.1	1.01	0.00223	535	339	74.2	0.3	24.2	35	1.68
15	5.3	201	.126	60.3	2.53	.00559	920	719	66.5	.3	62.5	35	2.36
16	5.3	200	.154	73.9	2.54	.00458	830	630	69.0	.6	63.0	47	2.46
17	5.3	200	.154	73.9	1.01	.00183	520	320	84.4	.6	24.2	47	1.81
18	6.9	204	.160	59.3	1.06	.00183	475	271	69.4	.3	24.3	28	1.53
19	6.9	200	.161	59.1	2.54	.00439	785	585	67.0	.4	62.3	38	2.12
20	6.9	202	.217	80.0	2.51	.00323	685	483	74.2	.8	61.7	41	2.19
21	6.9	201	.216	79.7	1.06	.00136	435	234	81.2	.7	24.4	36	1.64
22	11.0	199	.262	60.3	2.56	.00272	650	451	82.0	.5	60.7	28	1.85
23	11.0	201	.262	60.5	1.16	.00123	425	224	88.6	.5	25.1	28	1.46
24	11.0	200	.350	80.9	1.15	.00091	330	130	64.1	.9	25.1	28	1.40
25	11.0	198	.350	80.6	2.51	.00200	520	322	77.3	.9	59.4	26	1.78
26	24.0	199	.570	60.3	2.52	.00123	435	236	91.0	.8	53.6	21	1.46
(c) Fuel-injector configuration 3													
27	5.3	198	0.121	57.6	5.05	0.01162	1635	1437	70.1	0.6	1.6	77	4.00
28	5.3	206	.120	58.1	3.59	.00832	1350	1144	74.7	.6	.9	77	3.36
29	5.3	205	.120	58.0	1.69	.00391	905	700	90.9	.4	.6	51	2.36
30	5.3	205	.121	58.2	1.06	.00245	665	460	93.2	.3	.2	38	1.88
31	5.3	196	.158	75.3	3.55	.00623	1085	889	74.8	1.4	.6	--	4.08
32	5.3	196	.157	74.8	1.92	.00341	760	564	82.2	.6	.1	45	2.33
33	5.3	197	.158	75.4	1.27	.00222	610	413	91.1	.5	.1	37	1.96
34	6.9	200	.158	58.2	1.07	.00188	485	285	72.1	.4	.2	39	1.58
35	6.9	201	.159	58.5	3.23	.00566	965	764	69.4	.5	.3	46	2.48
36	6.9	201	.160	59.0	4.84	.00841	1340	1139	73.8	.5	.8	47	3.20
37	6.9	201	.158	58.1	6.10	.01075	1620	1419	74.4	.6	1.7	58	3.81
38	6.9	202	.157	57.8	6.15	.01092	1675	1473	76.1	.6	1.7	59	3.91
39	6.9	194	.218	79.6	1.35	.00172	505	311	86.0	.7	.2	36	1.80
40	6.9	201	.218	81.1	3.78	.00481	885	684	75.8	1.1	.2	56	2.85
41	6.9	205	.218	81.1	3.87	.00492	955	750	78.0	1.8	.3	--	3.70
42	11.0	198	.259	59.7	1.07	.00114	425	227	94.6	.6	-----	35	1.48
43	11.0	198	.259	59.7	3.98	.00427	860	662	76.8	.6	.1	35	2.25
44	11.0	200	.260	59.9	5.93	.00635	1170	970	81.4	.8	.9	46	2.88
45	11.0	199	.260	59.9	9.53	.01020	1650	1451	80.1	1.0	1.3	57	3.94
46	11.0	200	.350	80.9	1.49	.00118	390	190	75.1	1.0	.4	31	1.53
47	11.0	199	.350	80.7	3.84	.00305	710	511	83.0	1.2	.1	36	2.24
48	11.0	200	.350	80.5	5.96	.00474	980	780	85.4	2.7	.5	--	3.71
49	24.0	200	.570	60.3	2.44	.00119	440	240	96.4	1.2	.4	31	1.49
50	24.0	197	.570	60.0	17.89	.00872	1580	1383	87.7	1.8	2.4	43	3.73
(d) Fuel-injector configuration 4													
51	5.3	203	0.164	78.8	3.31	0.00561	980	777	72.2	1.4	7.5	--	3.76
52	5.3	203	.164	78.8	1.25	.00213	585	382	88.2	.5	1.6	35	1.91
53	6.9	206	.160	59.5	3.99	.00693	1125	919	70.5	.5	8.7	47	2.76
54	6.9	200	.164	60.2	6.12	.01039	1540	1340	71.9	.7	15.9	63	3.76
55	6.9	201	.164	60.3	1.73	.00294	655	454	75.8	.4	1.3	36	1.89

TABLE I. - Concluded. PERFORMANCE OF SINGLE FUEL-VAPORIZING COMBUSTOR WITH GASEOUS HYDROGEN

Run	Combustor inlet total pressure, in. Hg abs	Combustor inlet temperature, °F	Inlet air flow, lb/sec	Combustor reference velocity, ft/sec	Fuel flow rate, lb/hr	Fuel air ratio	Average combustor outlet temperature, °F	Average combustor temperature rise, °F	Combustion efficiency, percent	Total pressure drop through combustor, in. Hg	Fuel nozzle pressure drop, psi	Pressure loss coefficient, $\frac{\Delta p}{q}$	Density ratio, $\frac{\rho_{in}}{\rho_{out}}$
(d) Concluded. Fuel-injector configuration 4													
56	6.9	199	0.253	93.0	1.51	0.00165	470	271	78.7	1.1	1.8	42	1.95
57	6.9	197	.253	92.7	2.05	.00225	550	353	75.6	2.0	2.8	--	2.83
58	11.0	200	.262	60.5	1.07	.00113	385	185	69.2	.6	.5	34	1.41
59	11.0	199	.263	60.7	1.07	.00113	380	181	69.6	.5	.5	28	1.39
60	11.0	203	.261	60.5	3.52	.00375	775	572	77.7	.7	5.2	40	2.11
61	11.0	202	.261	60.4	5.57	.00593	1105	903	79.3	.8	11.9	45	2.75
62	11.0	201	.261	60.3	9.92	.01058	1660	1459	77.0	1.1	26.2	62	4.00
63	11.0	195	.437	100.1	1.49	.00095	360	165	84.0	2.0	.7	41	1.80
(e) Fuel-injector configuration 5													
64	5.3	198	0.126	61.2	1.47	0.00318	705	507	79.1	0.3	0.6	34	1.98
65	5.3	200	.124	59.5	3.20	.00717	1135	935	69.3	.4	2.6	48	2.82
66	5.3	200	.127	60.7	5.12	.01119	1615	1415	71.5	.5	6.0	58	3.90
67	5.3	203	.158	75.9	1.60	.00283	655	452	79.3	.5	.6	37	2.04
68	5.3	200	.158	75.5	2.82	.00498	910	710	74.8	.6	1.9	45	2.65
69	5.3	200	.158	75.6	3.56	.00627	1095	895	75.0	1.4	3.3	--	4.08
70	6.9	203	.162	59.8	1.19	.00204	555	352	84.5	.3	.3	28	1.67
71	6.9	202	.163	60.0	2.86	.00489	895	693	71.9	.4	1.6	37	2.31
72	6.9	201	.162	59.8	2.89	.00496	935	734	71.9	.4	1.6	37	2.39
73	6.9	203	.162	60.0	4.32	.00739	1220	1017	74.2	.5	3.5	46	2.96
74	6.9	204	.162	60.1	6.32	.01082	1650	1446	75.9	.6	6.9	55	3.88
75	6.9	200	.221	81.4	1.19	.00149	435	235	75.4	.7	.1	35	1.65
76	6.9	199	.221	81.1	3.71	.00467	885	686	75.5	1.0	2.5	50	2.80
77	6.9	203	.220	81.2	3.87	.00489	945	742	77.5	1.8	3.0	--	3.69
78	11.0	203	.251	58.2	1.33	.00148	460	257	84.1	.6	.3	37	2.65
79	11.0	203	.251	58.2	4.52	.00501	925	722	74.3	.6	2.2	37	2.34
80	11.0	201	.261	60.4	6.19	.00658	1180	979	79.4	.7	4.7	40	2.87
81	11.0	204	.258	60.0	8.90	.00958	1570	1366	79.6	.9	8.6	52	3.69
82	11.0	194	.348	79.7	1.49	.00119	395	201	69.0	1.0	.1	32	1.56
83	11.0	203	.348	80.8	4.64	.00370	800	597	81.6	1.3	2.3	41	2.46
84	11.0	202	.348	80.6	6.44	.00515	1015	813	82.8	2.5	5.2	--	3.63
85	24.0	197	.568	59.9	1.77	.00087	350	153	85.0	.9	.2	24	1.33
86	24.0	201	.565	59.9	9.03	.00444	950	749	87.4	1.3	4.6	34	2.41
87	24.0	197	.568	59.8	18.0	.00882	1525	1328	83.2	1.7	15.9	45	3.59
(f) Fuel-injector configuration 6													
88	5.3	200	0.126	60.2	1.06	0.00234	575	375	77.0	0.3	0.6	35	1.74
89	5.3	199	.127	60.8	2.43	.00531	925	726	70.0	.3	1.8	40	2.41
90	5.3	201	.127	60.7	3.59	.00788	1230	1029	69.6	.5	3.5	58	3.09
91	5.3	201	.127	60.7	5.24	.01151	1650	1449	72.0	.5	6.0	64	4.01
92	5.3	203	.159	76.6	1.07	.00186	555	352	94.1	.5	.6	37	1.84
93	5.3	200	.159	76.2	3.53	.00617	1055	855	72.4	1.4	3.3	--	3.96
94	5.3	202	.159	76.5	2.05	.00358	785	583	83.0	.6	1.0	44	2.37
95	6.9	203	.163	60.3	1.08	.00183	510	307	79.5	.3	.1	27	1.60
96	6.9	201	.163	59.9	3.42	.00584	1020	819	72.9	.5	2.3	46	2.59
97	6.9	203	.161	59.6	4.74	.00817	1330	1127	74.7	.6	4.5	56	3.23
98	6.9	201	.161	59.4	6.09	.01050	1615	1414	76.5	.7	6.7	65	3.90
99	6.9	203	.220	81.2	1.07	.00135	450	247	90.0	.6	.1	30	1.63
100	6.9	203	.218	80.5	3.07	.00392	795	592	76.1	.9	1.8	46	2.49
101	6.9	203	.218	80.5	3.79	.00484	920	717	74.7	1.9	3.2	--	3.70
102	11.0	202	.260	60.3	1.57	.00168	500	298	84.7	.5	.1	28	1.58
103	11.0	200	.260	59.9	4.06	.00435	885	685	80.3	.6	2.0	34	2.29
104	11.0	201	.261	60.4	6.58	.00700	1260	1059	81.1	.7	5.2	40	3.02
105	11.0	205	.262	61.0	8.80	.00933	1585	1380	82.1	.9	9.0	50	3.73
106	11.0	199	.346	79.7	1.96	.00157	465	266	81.5	1.0	.5	32	1.68
107	11.0	202	.347	80.3	5.96	.00478	955	753	81.2	1.6	4.2	51	2.94
108	11.0	200	.347	80.0	6.15	.00493	980	780	81.9	2.7	4.5	--	3.67
109	24.0	204	.567	60.4	8.32	.00407	900	696	87.5	1.3	4.1	34	2.31
110	24.0	196	.570	60.0	17.70	.00863	1540	1344	85.5	1.8	15.8	47	3.65
111	24.0	201	.568	60.2	2.31	.00113	430	229	92.8	1.0	.1	26	1.46

TABLE II. - DATA FOR COMPUTING CORRELATING PARAMETER $V_r/p_i T_i$

[Combustor temperature rise, 1200° F.]

Run	Inlet			Fuel	Correlation parameter, $V_r/p_i T_i$, ft, lb, sec, °R units	Combustion efficiency, percent
	Total pressure, in. Hg abs	Temperature, °F	Nominal reference velocity, ft/sec			
[a]1	15.0	102	[b]48.5	JP-4	82×10^{-6}	70.1
[a]2	20.0	110	[b]48.5		60	79.0
[a]3	25.0	130	[b]48.5		47	82.3
[a]4	30.0	150	[b]48.5		38	83.8
5	5.3	200	60	Gaseous hydrogen	244	73.6
6	6.9	200	60		187	74.3
7	11.0	200	60		117	81.0
8	24.0	200	60		54	88.9

[a]Ref. 4.

[b]Corrected to an area of 0.1965 sq ft.

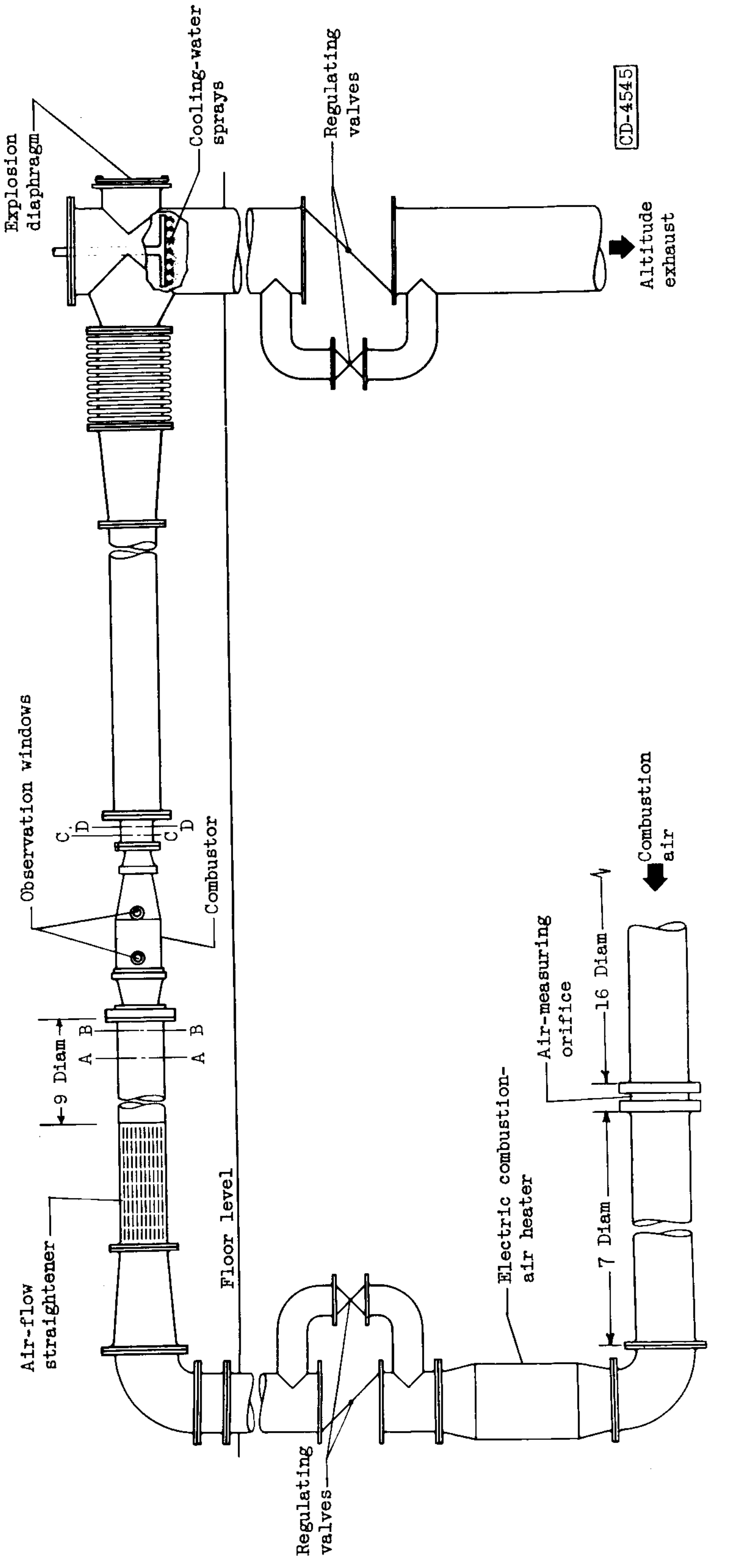
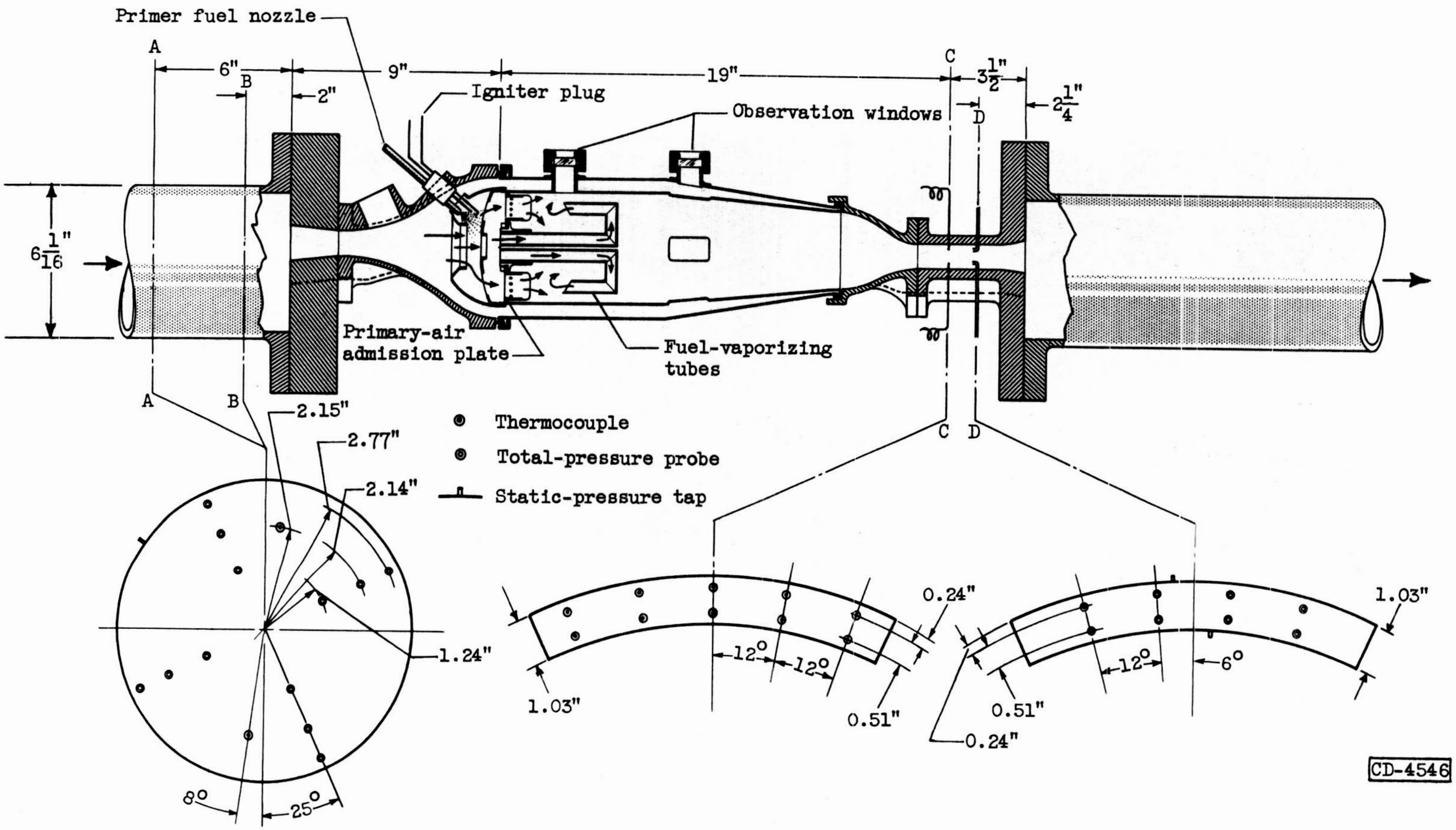


Figure 1. - Single-combustor installation showing instrumentation planes.



Plane A-A (Inlet total-pressure probes and static-pressure taps)

Plane B-B (Iron-constantan thermocouples)

Plane C-C (Chromel-alumel thermocouples)

Plane D-D (Exhaust total-pressure probes and static-pressure taps)

Figure 2. - Cross section of single combustor showing auxiliary ducting and location of temperature- and pressure-measuring instruments in instrumentation planes. (Main fuel-injector tubes are not shown.)

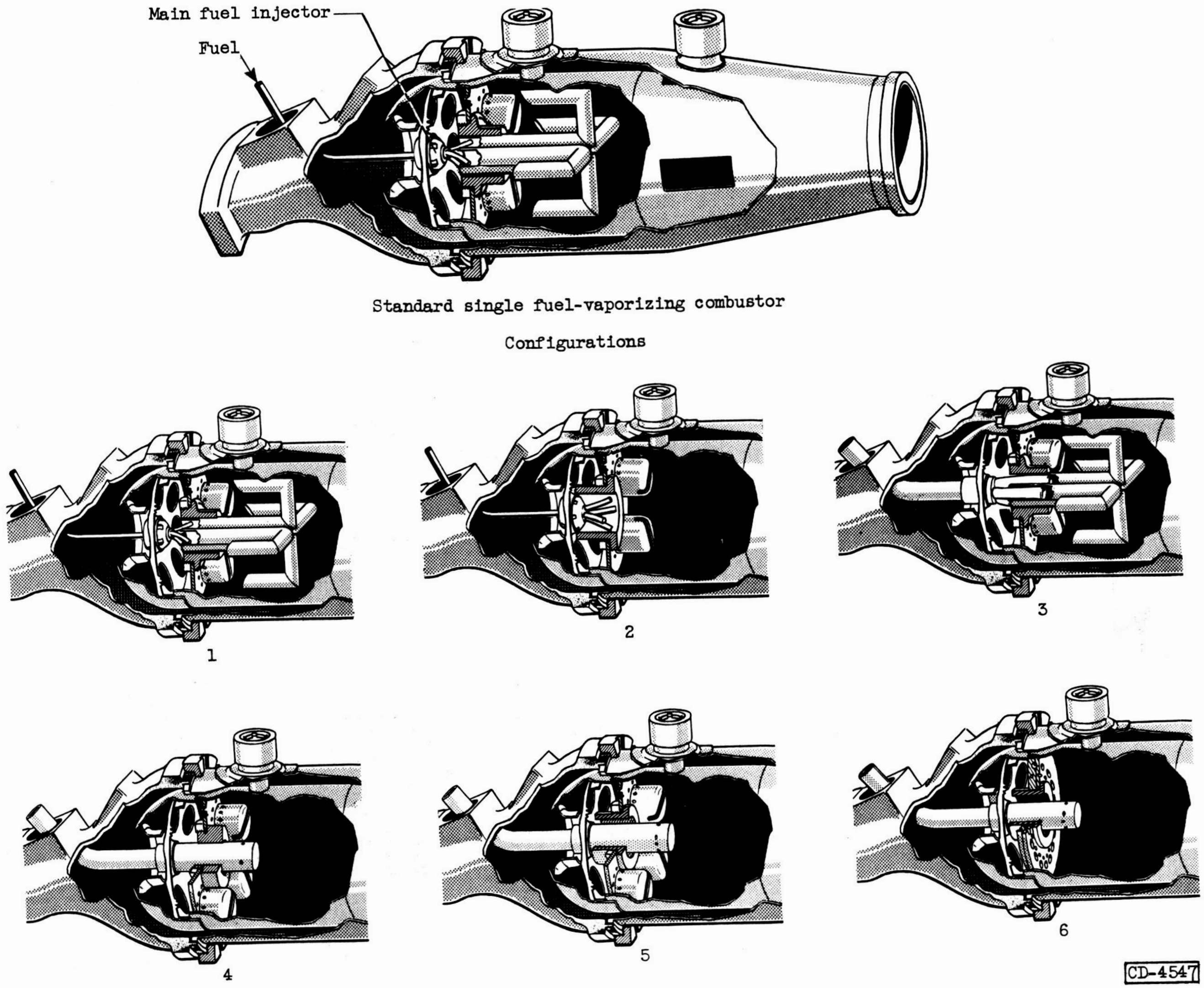
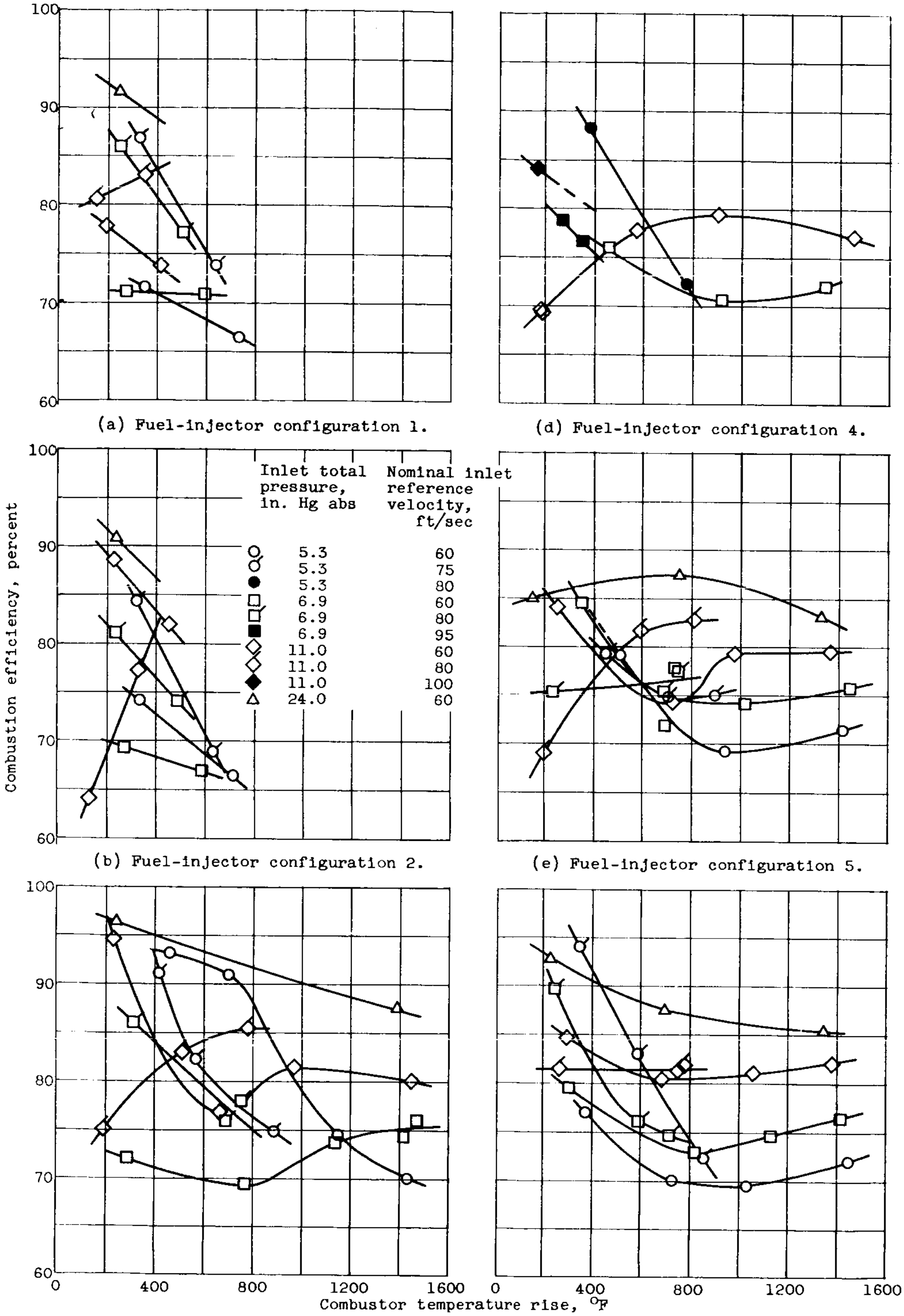


Figure 3. - Fuel-injector configurations used with gaseous hydrogen in a fuel-vaporizing combustor. (Primer fuel nozzle and igniter plug are not shown.)



(a) Fuel-injector configuration 1.

(d) Fuel-injector configuration 4.

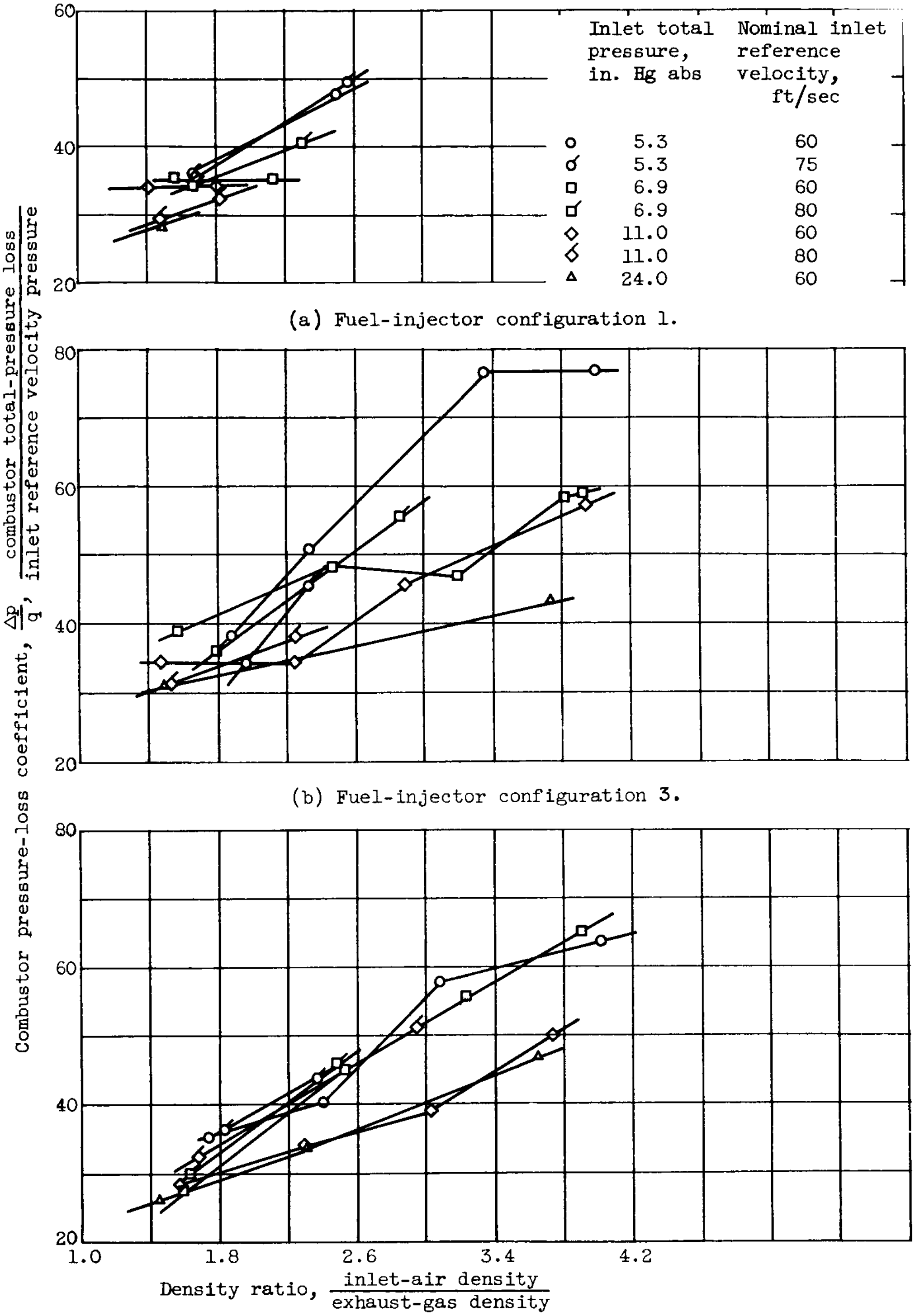
(b) Fuel-injector configuration 2.

(e) Fuel-injector configuration 5.

(c) Fuel-injector configuration 3.

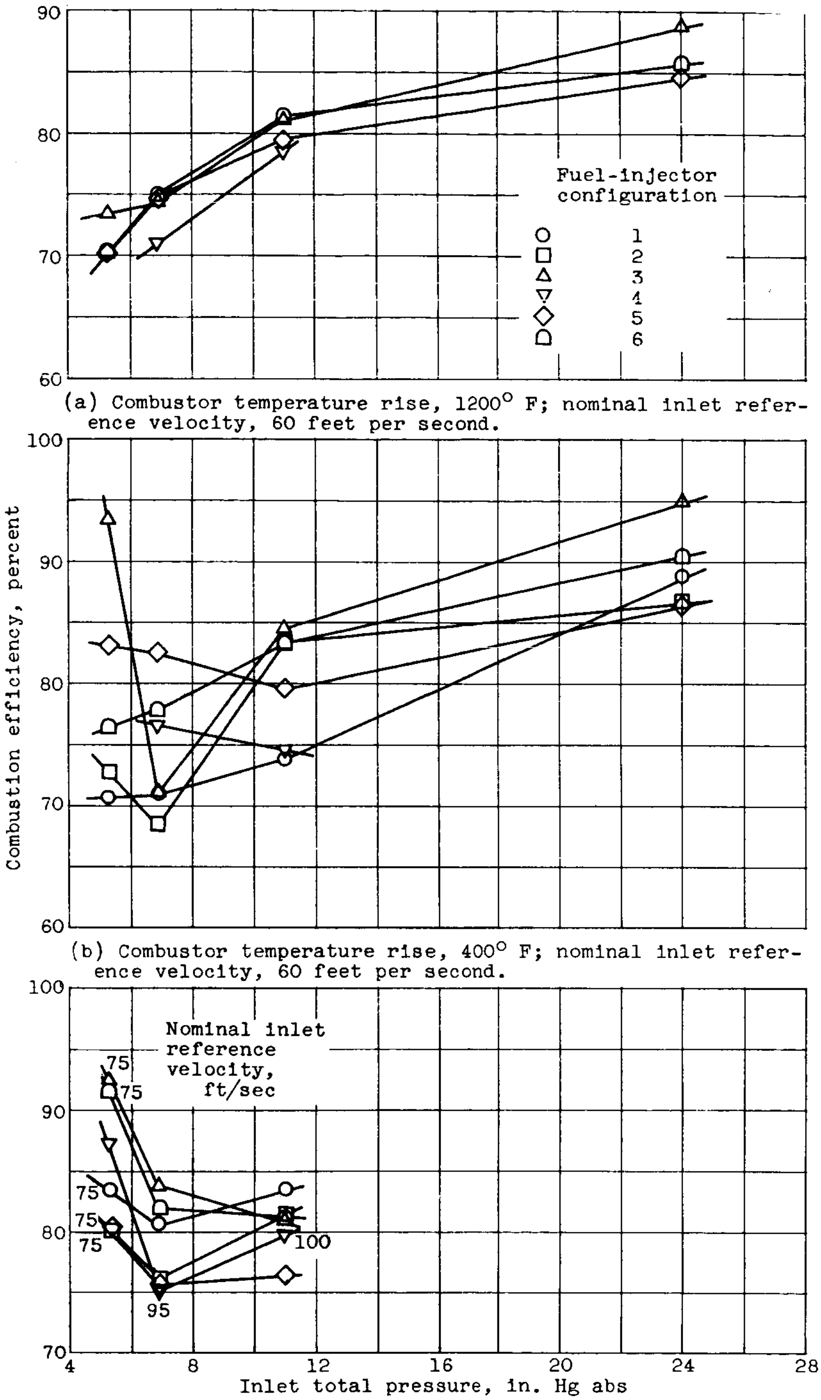
(f) Fuel-injector configuration 6.

Figure 4. - Variation of combustion efficiency with temperature rise for gaseous hydrogen in single tubular fuel-vaporizing combustor. Inlet-air temperature, 200° F.



(c) Fuel-injector configuration 6.

Figure 5. - Variation of pressure-loss coefficient with density ratio for gaseous hydrogen fuel in single tubular fuel-vaporizing combustor. Inlet-air temperature, 200° F.



(c) Combustor temperature rise, 400° F; nominal inlet reference velocity, 80 feet per second except where noted.

Figure 6. - Variation of combustion efficiency with combustor-inlet total pressure for gaseous hydrogen fuel in single tubular fuel-vaporizing combustor. Inlet-air temperature, 200° F.

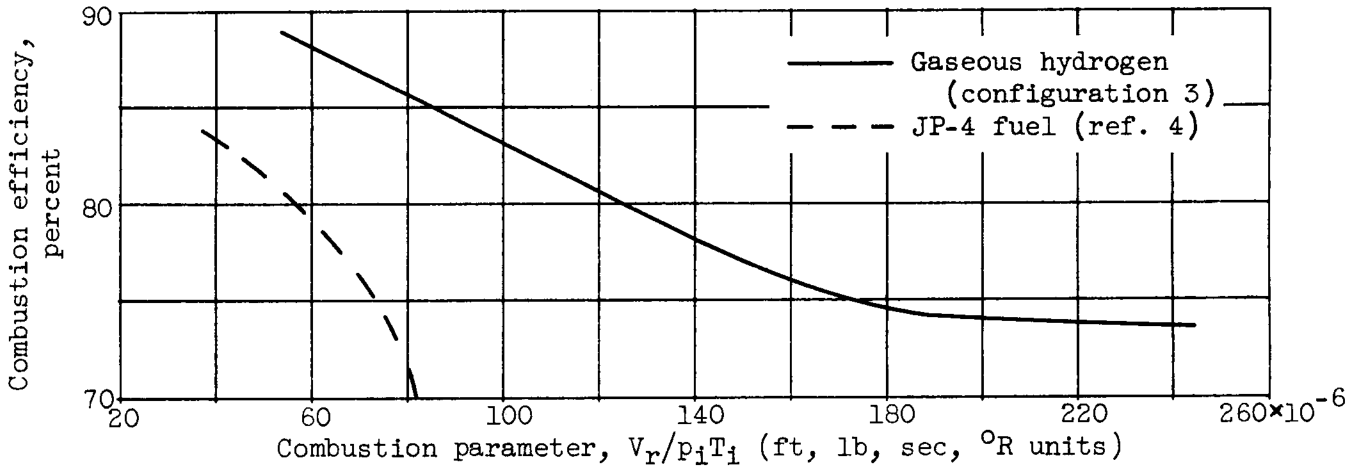


Figure 7. - Correlation of combustion efficiency with combustion parameter V_r/p_iT_i in single tubular fuel-vaporizing combustor. Combustor temperature rise, 1200° F.

NACA - Langley Field, Va.

UNCLASSIFIED

UNCLASSIFIED